

HUMAN/AUTOMATION TRADE METHODOLOGY FOR THE MOON, MARS AND BEYOND

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ABSTRACT

A consistent trade methodology can be created to characterize operations model alternatives for crewed exploration missions. For example, a trade-space with the objective of maximizing Crew Exploration Vehicle independence would have as an 'input' the category of analysis/decision to be made, and when the analysis/decision is required. For example, does the decision relate to crew activity planning or life support, and will it be made during trans-Earth injection, cruise, or lunar descent? Different kinds of decision analysis of the trade-space between human and automated decisions will occur at different points in a mission's profile. The necessary objectives at a given point in time during a mission will call for different kinds of response with respect to where and how 'automation' is expected to help provide an accurate, safe, and timely response. In this paper, a consistent methodology for assessing the trades between human and automated decisions on-board will be presented and various examples discussed.

INTRODUCTION

As we begin to use the Orion Crew Exploration Vehicle (CEV) first for missions to the International Space Station (ISS), and then to other low-earth orbit missions, we expect that despite Orion being a new spacecraft with significant potential for automation, it will be operated with a strong ground-based mission control. When the Orion is going to a lunar sortie or longer-term lunar mission, it will also have a strong real-time mission control support the crew. Due to communication time-delays, this will change when an Orion begins to enter interplanetary space, such as on a mission to a near-earth object (NEO). How would the location of the exploration mission drive the level of on-board mission automation, and how does that locus of authority impact how a mission is operated on-board and with earth-based support?

This paper assesses these issues and proposes a consistent trade methodology to characterize and

assess operations models for crewed exploration missions. In addition, the split between what decisions and operations a flight controller or a crew-member would perform versus the options to automate them is critical for mission success. The robustness of the mission and many of the associated costs are greatly impacted by on-board system capabilities and how well they are developed.

There is a spectrum of ways to perform crewed space exploration missions operations. At one end, the current NASA model assumes a strong, nearly always present mission control staff, with exceptionally detailed insight into moment-by-moment crew operations and all spacecraft systems and subsystems. The other end of this spectrum has been popularized by many science fictions television shows such as Star Trek, where the spacecraft and crew are completely autonomous from any control, insight or guidance from the Earth. In this paper, these modes are referred to as earth-based and on-board operations, respectively.

The "locus of authority" axis in Figure 1 illustrates a continuum of the interaction between human activity and automation. Humans can make decisions with automated support, e.g. calculating ramifications of human decisions, or the system can run in "fire and forget" mode, where humans provide goals or reference point for vast tracts of the expected operable space, and are only asked for input and guidance in special or extreme circumstances.

The "locus of control" axis shows the location of the decision or analysis process: Earth-based or On-board. On-board locus of control for is fundamental shift in crewed spacecraft.

To date, all NASA crewed missions been designed with the expectation and desire of comprehensive, earth-based mission operations capable of providing extensive knowledge and insight to the crew throughout the mission and in any circumstance. The most notable example of this was the Apollo 13

incident, when mission ops and engineering teams' ingenuity saved the crew's lives and enabled a safe

return to earth.

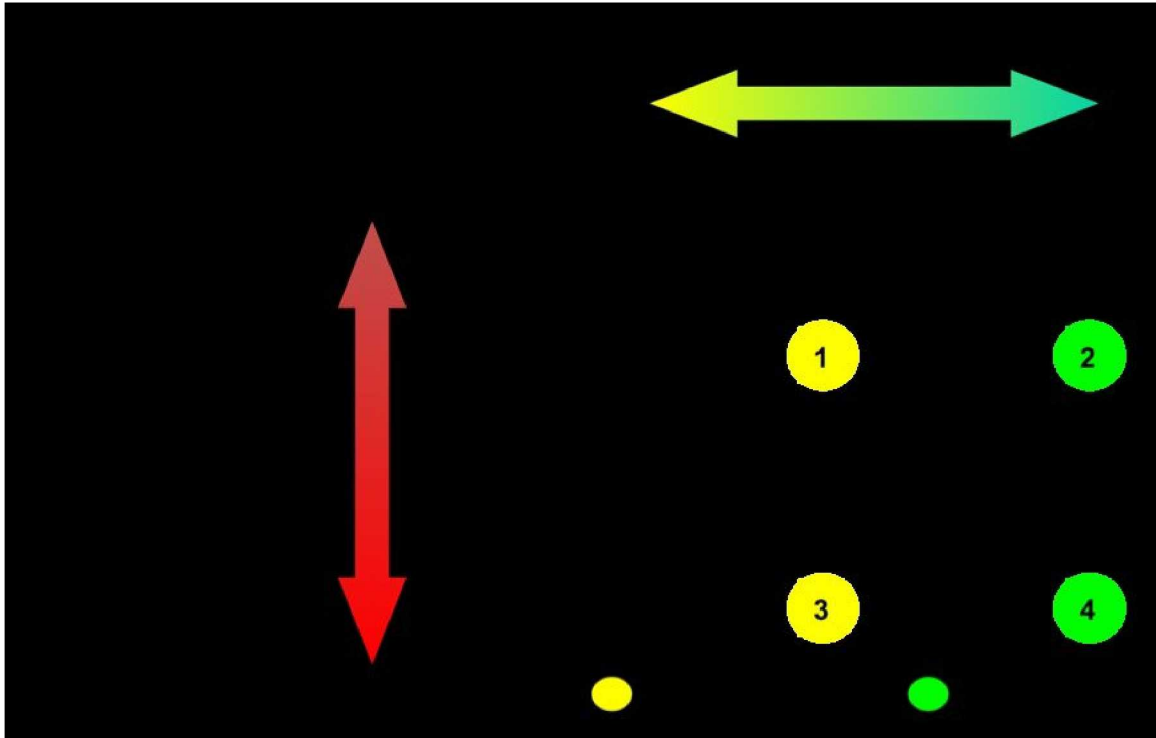


Figure 1: Four corners of outcome for Human Automation trades.

Note: The axes represent a continuum and are not binary-valued, this depiction provide a framework for considering trade-offs between automation and manual decisions/analyses.

To explore how mission profiles impact mission operations decisions, we can create trade-trees that portray ops model alternatives. Figure 2 shows what happens if our objective is to maximize the CEV crew independence. The 'input' to this trade-tree is the type of analysis/decision to be made, and its timing during the mission profile.

For example, does the decision have to do with crew activity planning, or life support? What is the mission phase? What information would go into the decision or analysis? Different kinds of decisions and analysis at different points in a mission's profile call for different answers on how automation could help provide an accurate, safe, and timely response.

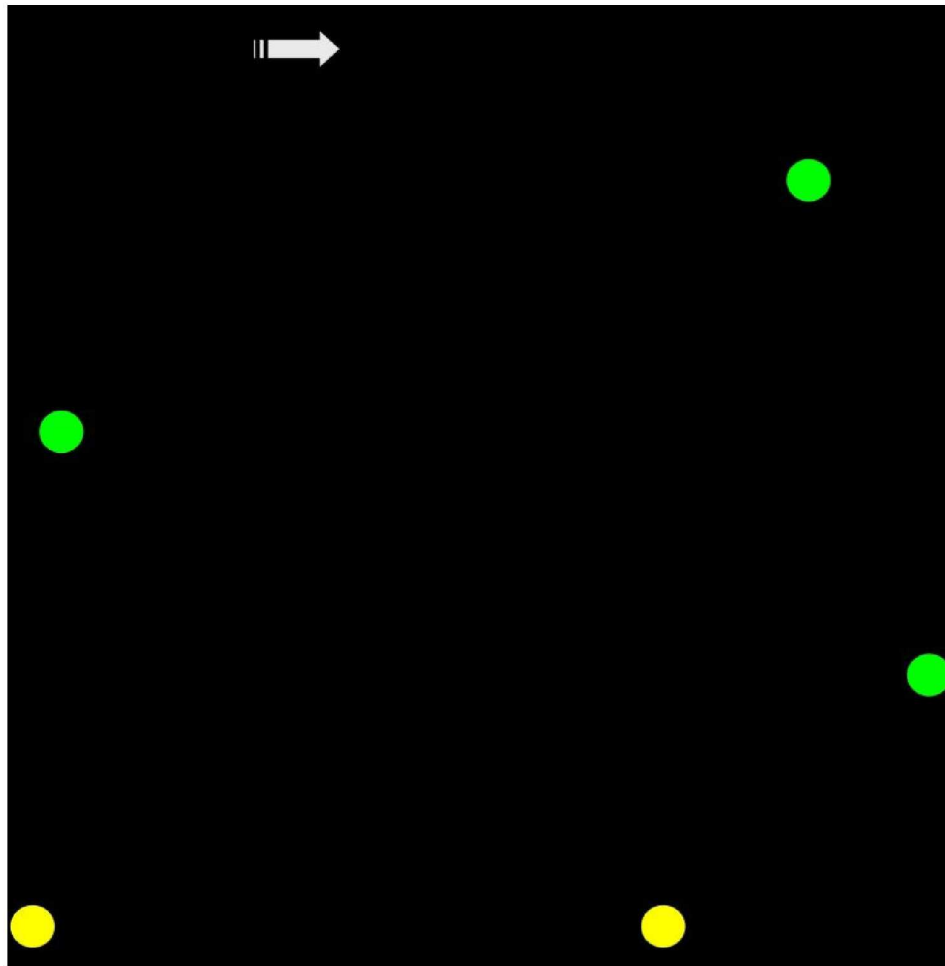


Figure 2: Trade-tree for maximizing CEV independence from Earth control.

Note: Green circles represent trade-tree exit points that should be studied with high priority, and yellow circles are medium priority.

Maximizing CEV independence (shown in Figure 2) would lead to an on-board operations capability that can effectively achieve mission objectives under a wide variety of circumstances. However, it could also be expensive to develop and introduce significant complexity to on-board computer system relative to present standards.

Figure 3 shows another trade-tree, this time with the objective of using Earth-based support to the greatest possible extent. The input to this trade-tree is the same

as shown in Figure 2, but the results are quite different. This time, whenever it's possible to leave a decision or analysis on Earth, that is what is chosen. This approach will likely yield an operations infrastructure that is more similar to the current Shuttle and ISS systems, and thus be quicker to construct, but the CEV will probably be less time-efficient, and it's dependence on support from Earth will reduce the variety of viable missions.

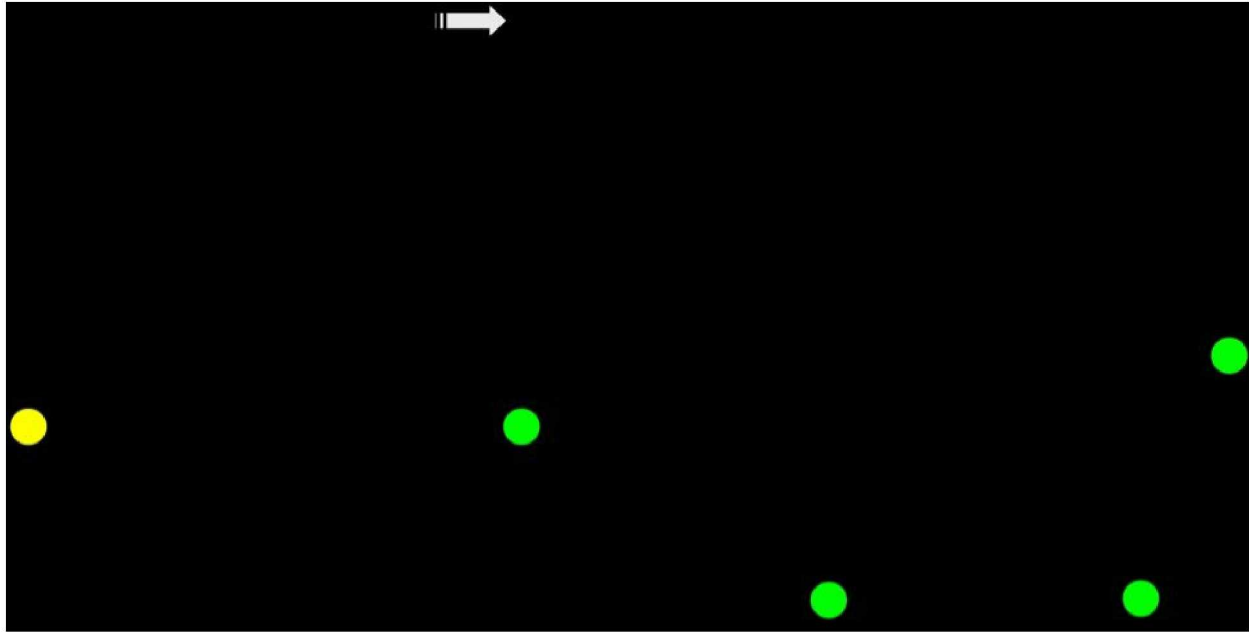


Figure 3: Trade-tree for maximizing Earth-based support.

Note: Green and yellow circles represent trade-tree exit points that should be studied with high and medium priority.

After reviewing the above two trade-trees, it becomes clear that Figure 1 provided a summary of all of the ‘exits’ in both trade-trees, and indeed, a summary of exits from all possible trade-trees. While many other trade-trees are possible, based on alternative objectives, all will eventually produce guidance regarding where a decision or analysis should be made (locus of control), and how humans, both flight controllers and crew, and automation participate together in making that decision (locus of authority).

The trade-tree outcomes in Figure 1 characterize all the options for localizing the making of decisions, and different trade-trees weight and prioritize these outcomes in different ways. For the discussion in this paper, we will consider the trade-trees for a crewed mission to a near-earth asteroid using the Orion CEV. This analysis will expose the types of decisions needed for earth-based operations and those necessary for on-board operations by the crew and support automation.

CONSTELLATION PROGRAM’S MISSION OPERATIONS

NASA Johnson Space Center’s (JSC) Mission Operations Directorate (MOD) manages and maintains the flight operations of all of NASA’s human space missions. Manned flight operations support is provided by the combination of several ground mission control centers around the U.S. and the World, primarily focused through the Mission Control Center (MCC-H) at JSC in Houston, Texas. With the

retirement of the Shuttle in the early 2010’s, MOD at JSC is in the initial stages of planning the Operations support activities associated with the new Orion for both the initial ISS visits and Lunar flights. MOD has stated a goal of manning the Orion’s flight support with approximately 50% of the manning currently required for Shuttle. This goal is based in part on the assumed simplicity of operations of Orion as compared to the Shuttle and on assumed increased automation within the spacecraft onboard systems. MOD is restructuring itself to be more efficient in support of the “Plan, Train, and Fly” activities associated with the Constellation Program (CxP), and are also investigating several technology infusion opportunities from across NASA to provide increased automation to the earth-based controllers. For example, the CxP Mission Operation Project Office is working with NASA Ames to create new intelligent systems for mission operations.¹ This paper utilizes the status of on-going 2009 work to premise future impacts on the space operations community.²

The flight phase of any mission includes the real-time flight operations with the Flight Director, Flight Controllers, Ground Controllers (for the facilities), the Engineering support, and in the case of ISS, the International Partner operations support and integration. Within the MCC-H, the team is structured such that the Flight Control Room (FCR) is the focus of all mission control, with the Flight Director,

CAPCOM (originally a contraction for Capsule Communications, but relevant to ISS also), the vehicle systems flight control specialists, and other specialists integrally involved in making the mission decisions. For most of the positions within the MCC-H FCR, there are support flight controllers in the Multi-Purpose Support Rooms (MPSR) within the MCC-H and in some cases in remote locations (such as the Canadian ISS Robotics Support). The detailed engineering support is provided by the Mission Evaluation Room, and this team can get support as needed from the systems experts at other centers, industry, and International Partners. MOD is assessing several new Ames-developed technologies and tools to enhance the real-time mission support environment including better search tools for flight-related information, a more interactive display building environment, and telemetry monitoring and agent-based support tools to off-load the work of the flight controllers. For all these technology improvements to the mission support ("Plan, Train, Fly), MOD is using the current ISS support environment as a test-bed.

Traditionally, past crewed NASA missions have been highly dependent upon earth-based mission operations. Crewed missions hardware and software systems are programmed to be capable of dealing with many unanticipated events, but most of the flexibility of the crewed missions comes from the crew itself and the ability of the earth-based flight controllers to adapt and handle any situation. This means that the primary responsibility for handling unforeseen situations always resides with humans, who are either onboard the spacecraft or in mission control.

MISSION OPERATIONS FLIGHT OPERATIONS IMPROVEMENT TEAM

In 2006, MOD chartered the Flight Operations Improvement Team (FOIT) to evaluate the processes, structures, and technical approaches that mission operations would need to support the Vision for Space Exploration, and the new Constellation Program.

The approach suggested by the FOIT automation team was to aim for full autonomy of future exploration missions from the earth. This means that the spacecraft and crew operate without intervention from the ground. This capability is clearly required for the future Mars missions, and the Lunar missions will provide a transition to this kind of operations. This autonomy may be achieved by a combination of automated and manual functions on-board, but requires no cues from the ground. The current MOD plan to support future operations, by necessity, is to evolve

their existing operations systems, processes and capabilities to support this future Orion and exploration autonomy concept. This means MOD wants to incorporate automation capability within ground operational practices at the beginning of the first flight of the Orion to the maximum extent possible. Preparing for this improved operations automation must be a staged process where it is necessary to assess what are the components of the future operations that are desired to be either on-board or earth-based³. Then knowing conceptually what are the future operational models to be striven for, to incorporate augmented automation capability within operational practices of the Mission Operations Directorate.

The FOIT study recommended several conceptual constraints upon future spacecraft, such as "Design a vehicle that can be automated safely." However the most significant recommendations were focused upon the overall operations strategy. This applies equally to the existing ground-based operational infrastructure used by MOD and the future goal of operations. These are (in part);

- (1) Utilize automation where it makes sense... and define up front what makes sense.
- (2) Let flight experience dictate what functions should be automated. Focus automation capability where requirements and vehicle functionality are clear and well understood. Phase in automation of complex operations as those operations mature.
- (3) Define roles & responsibilities up front. Clarify expectations and requirements for all phases of related development, delivery, and utilization. More specifically, clarify the transition points for authority and responsibility between all organizations involved in automation development and implementation.
- (4) Address interactions with other areas of MOD responsibility: MCC, recon, training, procedure development, ops planning.
- (5) Allocate responsibility for developing automation products that are not embedded in flight software to Mission Operations.

For example, to evolve from the existing practices operating the ISS required the assessment of what gaps exist in progressively making ISS more automated. This would initially not require more autonomy from the ground, but would mean that the current ISS

operations would be targeted for increase efficiency and automated systems would be looked at to reduce flight controller workload. By using the ISS operations as a demonstration and validation ground for the use of new technologies, MOD will be able to assess where, when and how additional advanced software systems will impact Constellation Program mission operations, and how those will enable the goal of an autonomy capable system for NASA's Exploration. The migration of autonomy-based mission support tools from the ground to the spacecraft will be a CxP Programmatic decision, but MOD is attempting to assess and support operational use of this technology both for ground operations improvements and for future spacecraft infusion.

The NASA mission community tends to be properly conservative about the use of new technology in mission-critical, and life-critical, situations. The automation necessary to support advanced operations is correctly perceived as involving new technology. Consequently, a realistic way to create acceptance of this new technology is to perform a series of analog operations using existing spacecraft, principally ISS, and then to begin using the technology in CEV missions as soon as practical.

In order to meet these new operational requirements it is critical that advanced operations are assumed from the beginning of the CEV development process. Operations concepts have system-of-systems implications for mission operations design, and tend to become "baked" into mission design, operational models, and culture.

CONSTELLATION PROGRAM'S CREWED NEO STUDY

The NASA Constellation Program study⁴ in 2006-2007 was to examine the flight elements of the Constellation Program, such as the Orion manned spacecraft as well as the Ares launch vehicles, for suitability for deep space missions beyond the Moon, and in particular, missions to NEOs. These missions can test spacecraft systems, operational techniques, crew experience, and acquire practical knowledge of NEO physical characteristics (e.g., internal structure and composition).

Previous studies were reviewed as a starting point for establishing mission objectives and identifying candidate target bodies and mission profiles. Mission objectives would be updated in consultation with Constellation Program mission designers and NEO scientists. The existing database of NEOs was mined to identify candidate targets. The study used special software to identify candidate NEOs with short trip

times and low Δv 's in the appropriate time frame (late 2010s through the 2020s). Performance characteristics of the Orion spacecraft and Ares launch vehicles were analysed against the mission requirements for a selected set of candidate targets.

Study Results Synopsis

At first order, the NEOs that are good targets of opportunity for initial piloted missions are those with the following characteristics:

- Earth-like orbits (low eccentricity and low inclination),
- close Earth approaches (i.e., ~ 0.05 AU of the Earth – a potentially hazardous object or PHO),
- slow rotation (i.e., rotation periods of ~ 10 hours or longer),
- single, solitary objects (nearly $1/6^{\text{th}}$ of all NEOs are binary objects)
- asteroidal origin (i.e., not a cometary or extinct comet, or transition object)

Some 35 candidate NEOs for exploration by piloted CEV missions were found in the current NEO catalog. Four launch options were assessed. These ranged from using an Ares 1/CEV with an EELV to launch a Centaur-class upper stage for NEO orbit injection, to the full Ares 1 and Ares V launch systems. Several trajectories and mission lengths from 90 to 180 days were examined.

CREWED NEO MISSION RATIONALE

Missions to NEOs reinforce the Constellation Program with a broad suite of benefits. Deep space operational experience (i.e., the manned CEV will be several light-seconds from the Earth) is critical for building a human presence in the inner solar system. The NEO missions are a risk reduction for Constellation space hardware for lunar missions as well as Mars missions. This mission would provide great confidence building for future mission scenarios (e.g., lunar poles and farside, other NEOs, and eventually Mars). Additionally the early in situ resource utilization (ISRU) evaluation from a NEO would help to validate or disprove the ideas for using asteroids as material resources. Of course there is a rich scientific return for understanding how the solar system formed. Sending a human expedition to a NEO, within the context of the exploration vision, will help NASA in many ways as this is an exciting new mission class for the Constellation Program, marking humanity's first foray beyond the Earth-Moon system.

CEV Science Capabilities:

A CEV-type mission will have a much greater capability for science and exploration of NEOs than robotic spacecraft. The main advantage of having piloted missions to a NEO is the flexibility of the crew to perform tasks and to adapt to situations in real time. Robotic spacecraft have only limited capability for scientific exploration, and may not be able to adapt as readily to certain conditions encountered at a particular NEO. The Japan Aerospace Exploration Agency's (JAXA) Hayabusa spacecraft encountered certain situations that were a challenge for both it and its ground controllers during close proximity operations at asteroid Itokawa. A human crew is able to perform tasks and react quickly in a microgravity environment, faster than any robotic spacecraft could (rapid yet delicate manoeuvring has been a hallmark of Apollo, Skylab, and Shuttle operations). In addition, a crewed vehicle is able to test several different sample collection techniques, and to target specific areas of interest via extra-vehicular activities (EVAs) much more capably than a robotic spacecraft. Such capabilities greatly enhance any scientific return from these types of missions to NEOs.

In terms of remote sensing capability, the CEV should have a high-resolution camera for detailed surface characterization and optical navigation. A light detection and ranging (LIDAR) system would be essential for hazard avoidance (during close proximity operations) and detailed topography measurements. In addition, the CEV should be outfitted with a radar transmitter to perform tomography, enabling a detailed look at the interior structure of the NEO. Given that several NEOs appear to have a high degree of porosity (e.g., Itokawa is estimated to be 40% void space by volume), it is important to measure this characteristic of the target NEO. Such information on its internal structure not only has implications for the formation and impact history of the NEO, but also may have implications for future hazard mitigation techniques.

Another advantage of the CEV is the capability to precisely place and re-deploy relatively small scientific packages on the surface of the NEO. Such packages as remotely operated (or autonomous) rovers with one or two instruments could greatly enhance the amount of data obtained from the surface, and fine-tune the site selection for subsequent sample collection. Other packages that may be deployed could be in situ experiments designed to test such technologies as surface anchors/tethers, drills/excavation equipment, or material extraction equipment. The CEV could also deploy a transponder to the surface of the object for a long-term study of the NEO's orbital motion. This

could be particularly useful for monitoring objects that have the potential for a possible future Earth impact.

The crew has the added advantage of EVA for sample collection during close proximity operations. The ability for the crew to traverse and collect one or more macroscopic samples from specific terrains on the surface of an NEO is the most important scientific aspect of this type of mission. Having a human being interacting in real-time with the NEO surface material and sampling various locales in context would bring a wealth of scientific information on such things as particle size, potential space weathering effects, impact history, material properties, and near-surface densities of the NEO.

CREWED NEO MISSION HUMAN/AUTOMATION TRADE-TREES

As we look beyond the space station program and past the moon towards the exploration of the inner solar system, near-Earth asteroids offer a feasible, attractive stepping stones to Mars and beyond. Piloted human missions to NEOs prior to human exploration of Mars can provide unique opportunities to validate mission technologies and acquire deep space operational experience unobtainable elsewhere.

< This portion of the material is in development and incomplete for this paper draft. The intent is to pick several normal engineering and scientific decision processes and determine the criteria for assessing whether they are better done earth-based or on-board, and what are they break points that would require them to remain earth-based, or force them to be on-board. Communication delays, and speed of response are several issues that will drive this assessment. >

CONCLUSIONS <DRAFT>

As crewed missions go beyond low-earth orbit and begin to enter interplanetary space, the time-delay for communication with earth will constrain the existing mission operations paradigm from a solely earth-based system to more and more on-board automation and crew autonomy. For a first step into this realm, the operational benefits alone of a human venture into deep space make a mission to a NEO a valuable prospect as a precursor to future Mars missions.

ACKNOWLEDGMENTS

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